Combining action observation and motor imagery improves eye-hand coordination during novel visuomotor task performance

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Abstract

In the present study we compared the effectiveness of concurrent action observation and motor imagery (AO+MI), observing with the intent to imitate (active observation; AO) and passive observation (PO) training interventions for improving eye-hand coordination. Fifty participants were assigned to five groups (AO+MI, AO, PO, physical practice (PP); control) and performed a visuomotor rotation task, whilst eye movements were recorded. Each participant then performed 20 task trials in a training intervention before repeating the visuomotor rotation task in a post-test. As expected, physical practice produced the greatest improvement in task performance and eye-hand coordination. However, in comparison to the control group, AO+MI training produced a statistically significant increase in both task performance and eye-hand coordination, but no such improvements were found following AO or PO.

Introduction

The observation of an action is widely accepted to activate similar, but not identical, neural structures to those active during the physical execution of the same movement (Hardwick, Caspers, Eickhoff, & Swinnen, 2018). This has led to suggestions that during the observation of actions, a motor representation of that movement is activated in the observer's motor system (Rizzolatti, Fogassi, & Gallese, 2001). Action observation (AO) has, therefore, been proposed as a simulation technique that has utility for motor (re)learning by facilitating neuroplastic changes in motor pathways (Buccino, 2014). Consequently, researchers have tested the efficacy of AO interventions in a variety of motor (re)learning settings, and this research indicates that it may offer clinical benefits for movement in stroke patients (Ertelt, 2007), upper limb amputees training with prosthetics (Cusack et al., 2016) and Parkinson's disease patients (Pelosin et al., 2010).

While previous research has used passive observation (e.g., watch the action) and active observation (e.g., watch the action with the intention to imitate) instructions (Wright, McCormick, Williams, & Holmes, 2016), recent research has suggested that the most effective method for delivering AO interventions is by combining the technique with concurrent motor imagery (AO+MI: Eaves, Riach, Holmes & Wright, 2016). MI involves the covert mental rehearsal of action execution (AE), typically in the absence of physical movement (Mulder, 2007). The rationale provided for combining both motor simulation techniques would seem intuitive. First, AO+MI produces increased cortico-motor activity compared to when AO or MI are performed in isolation (Eaves et al., 2016). Second, in contrast to MI, AO allows experimental control of the clarity, vividness and perspective of the image (Holmes & Calmels, 2008), and as AO does not require the participant to generate or maintain the visual aspects of an image, it allows them to focus their resources exclusively on generating kinesthetic imagery alongside the observation (Eaves et al., 2016). Finally, AO+MI has been shown to produce a positive effect on performance across a variety of motor activities, including the imitation of hand movements (Bek, Poliakoff, Marshall, Trueman, & Gowen, 2016), the recovery of upper limb function following stroke (Sun, Wei, Luo, Gan, & Hu, 2016) and strength (Scott, Taylor, Chesterton, Vogt, & Eaves, 2017), balance (Taube, Lorch, Zeiter, & Keller, 2014) and sports tasks (Romano-Smith, Wood, Wright & Wakefield, 2018).

Despite these positive findings, little is understood about how AO+MI facilitates skillful movement in such tasks. Although research has indicated increased activity in motor regions of the brain associated with AO+MI relative to independent AO or MI (Eaves et al., 2016), it is currently unclear how this would serve to facilitate motor skill learning. One possible explanation is offered by Jeannerod's (2001) simulation theory. In this theory, Jeannerod proposed that a functional equivalence exists between AO, MI and AE, whereby all three action states are associated with activity in similar neural structures. Research using neuroimaging techniques has provided support for this theory by demonstrating that several areas known to be active during action execution, such as the dorsal pre-motor cortex, supplementary motor area, superior parietal lobe and intraparietal sulcus, are indeed active during both AO and MI (Grezes & Decety, 2001; Filimon, Nelson, Hagler, & Sereno, 2007, Munzert, Zentgraf, Stark, & Vaitl, 2008). However, more recent evidence indicates that there are differences in how the two simulation states of AO and MI activate the motor system. For example, using multi-voxel pattern analysis, Filimon, Rieth, Sereno, & Cottrell (2015) demonstrated that lateral and posterior regions of the dorsal premotor cortex and anterior regions of the ventral premotor cortex are more active during AO, whilst anterior regions of the dorsal premotor cortex and posterior regions of the ventral premotor cortex are more active during MI. Similarly, in a meta-analysis of neuroimaging experiments, Hardwick, et al., (2018) reported that MI was associated with increased activity in the premotor cortex and supplementary motor area than AO. They also reported that AO was not associated with activity in any sub-cortical structures, whilst MI was associated with activity in the bilateral putamen and cerebellum. Consequently, the inclusion of motor imagery instructions in AO+MI interventions may promote increased and more widespread activity throughout the motor regions of the brain than which occurs through either passive or active observation interventions. This increased neural activity may facilitate the development of internal motor representations for specific actions, contributing to improved performance following AO+MI interventions.

Given the similar, but not identical, neural activity during AO, MI and AE, similar eye movements to those produced during AE should be recordable during simulation conditions. Indeed, evidence suggests that eye movements are similar during AE and MI (Heremans et al., 2008), AE and AO (Flanagan & Johansson, 2003) and MI and AO (McCormick, Causer & Holmes, 2012). Taken together, this suggests that these similar eye movement patterns may be indicative of a shared neural network that is used to plan and control visually guided actions. As AO+MI allows for the provision and control of the visual elements of simulation, attentional resources are able to be devoted to the kinesthetic aspects of a movement, which may serve to develop sensorimotor mapping rules that include the encoding of associated visuomotor programs.

However, little is currently known as to *how* AO+MI may be used to facilitate the development of effective eye-hand coordination. During the skilled performance of daily activities, gaze is directed towards objects of intended interaction as vision precedes action in a feedforward, proactive, manner (Land, 2009). Such coordination between eye and effector movement develops during the learning of a new skill. For example, Sailer, Flanagan and Johansson (2005) investigated this development as participants learned a challenging and novel visuomotor adaptation task. In this task, participants were required to move a cursor to targets displayed on a computer screen. Participants manipulated the cursor by applying isometric forces and torques to the tool held freely between the two hands. Results demonstrated that in the early stages of learning, eye movements tended to fixate the cursor, visually monitoring it as it approached the target. When the skill had been mastered, cursor movement was not attended to, and eye movements tended to be target focused in nature, enhancing performance. Therefore individuals learn to program spatially congruent eye and motor commands, so that fixations on objects precede motor actions and provide visually acquired goal related information to the motor systems (Land, 2009; Neggers and Bekkering, 2000; Sailer, et al, 2005). Task-specific (goal-directed) eye movements of this nature support the planning and control of manual action and are therefore indicative of top-down attentional control and task expertise (Land, 2009). Similar development of effective eye-hand coordination have been reported during real-world tasks like the learning of surgical skills (Wilson et al., 2010) and when learning to use a prosthetic hand (Parr, Vine, Harrison, & Wood, 2018).

Despite this proactive gaze behavior being shown to manifest during action observation (Sciutti et al., 2011), no studies have examined if/how AO+MI can be used to facilitate the development of eye-hand coordination and improve task performance. Therefore, in this study, we examined the effect of AO+MI for the development of eye-hand coordination during the performance of a novel visuomotor adaptation task. Given the more widespread neural activity associated with AO+MI, we hypothesized that this would lead to significantly faster adaptation compared to the other simulation conditions. Secondly, we expected that this improvement in performance would be reflected in the development of a proactive gaze strategy with the AO+MI group displaying significantly more target-focused gaze strategies after training, compared to the other simulation conditions (Sailer et al., 2005).

Method

Participants

Fifty right-handed participants (28 male and 22 female; age *M* = 24.8, *SD* = 4.73 years) with normal or corrected-to-normal vision, volunteered to take part in the experiment. Participants gave their written informed consent prior to taking part and the experimental procedures were granted ethical approval by the local university ethics committee.

Task

Participants performed an experimental task that was an adaptation of the virtual radial Fitts' task (Heremans et al., 2011). The goal of the task was to use a stylus to guide sequentially a cursor to a series of target squares whilst under the constraints of an 180^{o} visuomotor x-axis reversal (see Figure 1). The reversal resulted in any leftward movements of the stylus on the screen producing an equal rightward movement of the cursor, and vice-versa. Each sequence consisted of three squares (7 mm x 7 mm) that were presented in a radial pattern on the screen (132 mm apart). This gave an index of difficulty of 4.3 bits based on the Shannon formulation. Participants started at the 'home' target square located in the bottom center of the screen (right panel, Figure 1) and then moved to the next target square in each sequence highlighted in yellow. An auditory chime played each time the cursor was successfully guided onto the appropriate target to indicate it had been hit. Once all three onscreen squares were hit and the cursor returned the home square, a new three-square pattern was presented. In total, eight sequences were presented and successfully hitting all 25 targets represented one full trial.

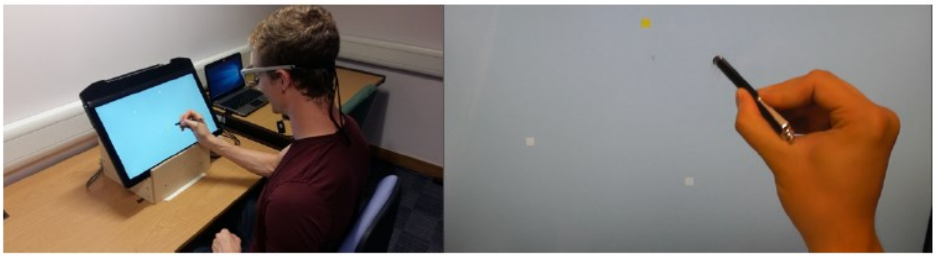

Figure 1. The left-side image shows a participant using the stylus and touchscreen to perform the experimental task. Each participant wore eye-tracking glasses during each phase of the experiment. The right-side image shows a screenshot of the action observation video used in the AOMI, AO and PO training interventions.

Apparatus

Testing was performed on a vertically oriented Dell ST2220T touchscreen monitor (Dell, Round Rock, TX) with a 480 mm x 270 mm visual display, situated 210 mm from the edge of the table where the participant was seated (see Figure 1). This monitor had been modified to report input along the x-axis as reversed thereby providing participants with an 180° visuomotor reversal on only one plane of movement that had to be negotiated in order to complete the task successfully. This was introduced in order to present participants with a novel task that would disrupt eye-hand coordination (Sailer et al., 2005). The adapted virtual radial Fitts' task was produced using DMDX software (Forster & Forster, 2003) which allowed the automatic presentation of the next target in the sequence once the previous target had been hit. The equipment had a temporal resolution of 15ms and a spatial resolution of one pixel on a 1280 x 720 resolution monitor.

Participants' gaze behavior was monitored using SMI ETG 2w eye tracking glasses and iView ETG 2.7 software (SensoMotoric Instuments, Teltow, Germany). The system comprises a pair of lightweight glasses that track participants' binocular eye movements at a sampling rate of 60 Hz with a gaze position accuracy of 0.5°. This was calibrated for each participant prior to the pre-test using a 3-point calibration procedure and accuracy of this calibration was monitored prior to each trial by instructing participants to fixate on points on a calibration grid that represented the spatial arrangement of the target sequences. If, during the session, the quality of the calibration was deemed to have deteriorated then the calibration procedure was repeated before testing continued.

Procedure

Pre-test

All participants performed a familiarization trial that consisted of guiding the cursor to hit three targets under the constraints of the visuomotor reversal in order to establish the goal of the task and the presentation of the target sequence. Only three targets were used to minimize the level of adaptation to the x-axis reversal. Prior to the start of the trial participants were instructed to guide the cursor to the targets using the stylus and to attempt to complete the sequence as quickly and accurately as possible (Rentsch & Rand, 2014). Following this participants were then fitted with eye-tracking glasses and performed a pre-test consisting of one 25-target trial. Following completion of the trial participants immediately began the training intervention to which they had been randomly assigned.

Training Interventions

Physical practice group. Participants in this group completed 20 trials of physical practice of the same 25-target task completed at pre-test (a total of 500 target hits; Sailer et al., 2005). This number of trials was deemed appropriate as most participants may adapt to small visuomotor rotations within 240 attempts (Krakauer, Ghilardi, & Ghez, 1999) but adaptation to 180° visuomotor reversal has been shown to take longer (Werner & Bock, 2010). Participants were given a 30 second rest after completion of each trial. Completing this training phase took approximately 20 minutes.

Intervention Groups. In each of the intervention conditions participants watched a video of an expert model completing four trials of the pre-test 25-target task, filmed from a first person visual perspective using a static camera in which only the model's hand and arm were visible (right panel, Figure 1). This perspective was selected in order to increase the visual congruence between the observed action and physical performance (Holmes & Collins, 2001) and has been used in similar task protocols (Lim, Larssen, & Hodges, 2014; Ong and Hodges, 2010; Ong, Larssen, & Hodges, 2012). The expert model had previously performed the task over 100 times and consistently completed the task within 40 seconds. An expert model was selected to show repeated trials of successful task execution in order to minimize variability (Blandin & Proteau, 2000) and previous visuomotor adaptation research has shown both novice and expert models to produce almost identical outcomes (Ong and Hodges, 2010; Ong et al., 2012). The video was shown five times for 20 observed task completions totaling 500 target hits. Prior to watching each video participants were given specific instructions depending on the experimental condition to which they had been assigned. Participants in the AO+MI group were instructed to "actively imagine that you are performing the movement as you observe it. Specifically, try to imagine the feelings in your muscles associated with gripping the stylus and moving your arm across the screen". Participants in the AO group were instructed to "observe the movement closely as you will be asked to imitate the movement sequence later in the experiment", whilst participants in the PO group were instructed to "observe the movement sequence shown on screen" and given no further explicit instructions. In all three intervention groups, participants were asked to remain still whilst they engaged with their intervention videos. Following each video, participants were given a 30 second rest. Completion of each training intervention took approximately 20 minutes.

Control Group. Participants in this group watched a 20-minute video of a nature documentary that contained no human motor content (Buccino, 2014).

Post-test

Participants then performed a post-test that was identical to that completed at the pre-test.

Measures

Performance

Performance was measured as the time (in seconds) taken to complete one trial of 25 target hits. Previously, researchers (e.g., Chan & Hoffman, 2016) have used task completion time as an indicator of improvement in motor performance in similar goal-directed aiming tasks.

Gaze control

Eye tracking videos of each pre-test and post-test trial were analyzed using BeGaze 3.7 software (SMI, Teltow, Germany). Areas of interest (AOI) were assigned to each target and the cursor. Targets were defined as the yellow highlighted square in each sequence. Analysis was performed manually on a fixation-by-fixation basis allowing each fixation to be assigned to the appropriate AOI. Fixations were defined as gaze dispersed over less than 3^{o} of visual angle for a minimum of 80 ms. The total duration of all target and cursor fixations at pre-test and post-test was determined and a target locking measure was then calculated by subtracting the percentage of cursor fixation time from the percentage of target fixation time. A more positive score reflects more time fixating on targets whereas a negative score reflects more time spent fixating the cursor. A score of ‘0’ reflects equal time spent fixating the cursor and targets and represents a ‘switching strategy’. This has been shown to be a reliable measure of eye-hand coordination in studies (1) examining expertise in prosthetic hand control (Parr et al., 2018) and surgery (Wilson et al., 2010); (2) in studies that have examined the development of eye-hand coordination (Parr, Vine, Wilson, Harrison & Wood, 2019; Wilson et al., 2011); and (3) in studies examining the effect of pressurized performance environments on eye-hand coordination (Vine, Freeman, Moore, Chandra-Ramanan, & Wilson, 2013).

Data analysis

Separate one-way ANOVAs were used to analyze the percentage of change in completion time and target locking score. Greenhouse-Geisser corrections were used where the assumption of sphericity was violated. Post hoc analyses were conducted using pairwise comparisons with the Bonferroni adjustment. Effect sizes are reported as partial eta squared (η_p^2). A linear regression was also performed to assess if any improvements in target locking score predicted improvements in task completion time.

Results

Preliminary analysis

One way ANOVAs performed on the pre-test performance and eye gaze data revealed no significant differences between groups for task completion time (p = .975) or target locking score (p = .691) (Table 1).

Table 1. Mean scores for completion time and target locking score.

Group	Completion time (s)			Target locking score (%)		
	Pre-test	Post-test	Percentage of improvement from pre-test	Pre-test	Post-test	Percentage of improvement from pre-test
AO+MI	95.62	50.77	42.79	-25.23	22.42	47.65
	(11.89)	(3.65)	(4.60)	(14.57)	(11.72)	(9.03)
AO	93.36	57.54	35.47	-26.93	2.91	29.84
	(9.95)	(4.14)	(4.16)	(10.66)	(12.07)	(8.12)
PO	92.66	54.00	35.07	-31.63	-2.23	29.40
	(16.07)	(4.67)	(4.84)	(12.38)	(14.01)	(6.58)
PP	89.51	30.57	64.40	-45.48	30.33	75.81
	(6.06)	(3.65)	(4.62)	(7.54)	(14.95)	(11.48)
Control	100.58	75.96	24.27	-31.62	-20.07	11.55
	(13.32)	(9.91)	(1.69)	(5.18)	(4.98)	(4.35)

Performance

A significant difference between groups ($F_{(4, 49)} = 12.99$, $p < .001$, $\eta_p^2 = 0.54$) was found for the percentage change in task completion time (Table 1). Pairwise comparisons with the Bonferroni adjustment revealed that the PP group reduced their completion time significantly more than all the other groups (AO+MI, $p = .006$; AO, $p < .001$; PO, $p < .001$; control, $p <.001$). In addition, whilst the AO+MI group showed significantly greater reductions in completion time compared to the control group ($p = .03$), no such changes were found in the AO or PO groups (see Figure 2a).

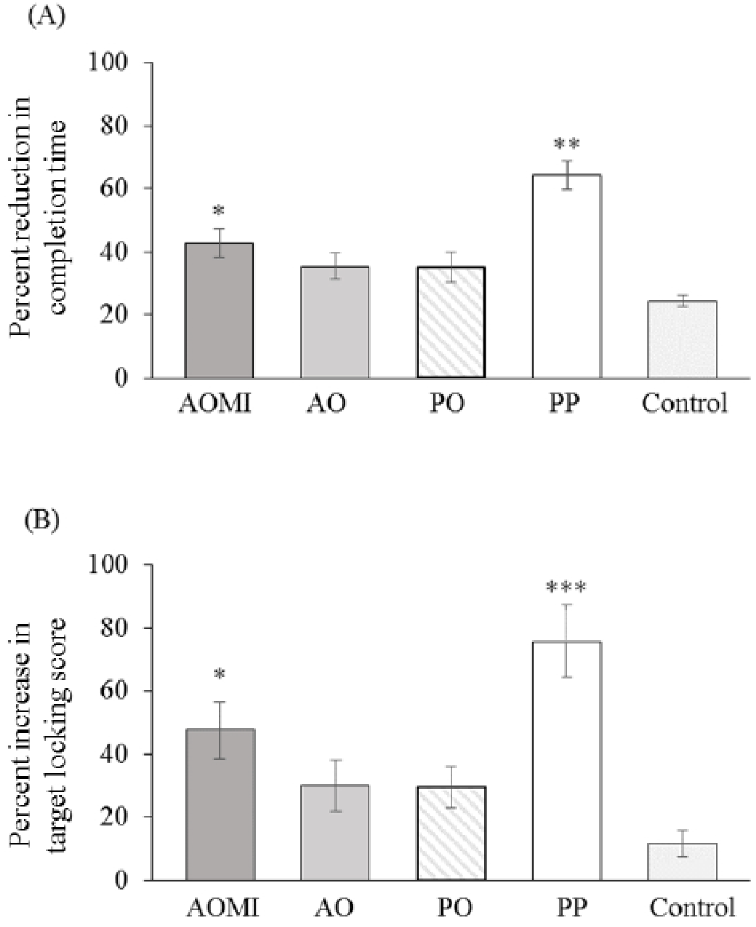

Figure 2. Mean scores for (A) percent reduction in completion time and (B) percent increase in target locking score. Error bars represent standard error of the mean. * indicates a significant difference from control (p = .03), ** indicates a significant difference to all groups ($p \leq .006$), *** indicates a significant difference to AO, PO, and control ($p \leq .003$)

Gaze control

A significant difference was found between groups in target locking score ($F_{(4, 49)}$ = 8.64, $p < .001$, $\eta_p^2 = 0.43$). Pairwise comparisons with the Bonferroni adjustment indicated that participants in the PP group acquired a significantly higher target locking score than the AO (p = .003), PO (p = .003), and control (p <.001) groups (Table 1). However, there was no significant difference between the PP and AO+MI groups (p = .20). Furthermore, whilst the AO+MI group increased their target locking score to a significantly greater extent than the control group (p = .03), no such improvement was found in the AO and PO groups (see Figure 2b).

Regression

This analysis indicated that the percentage of increase in target locking score was a significant predictor of the percentage of decrease in completion time ($F_{(1, 49)} = 61.47$, $R^2 = .56$, b = .41, $p < .001$) (see Figure 3).

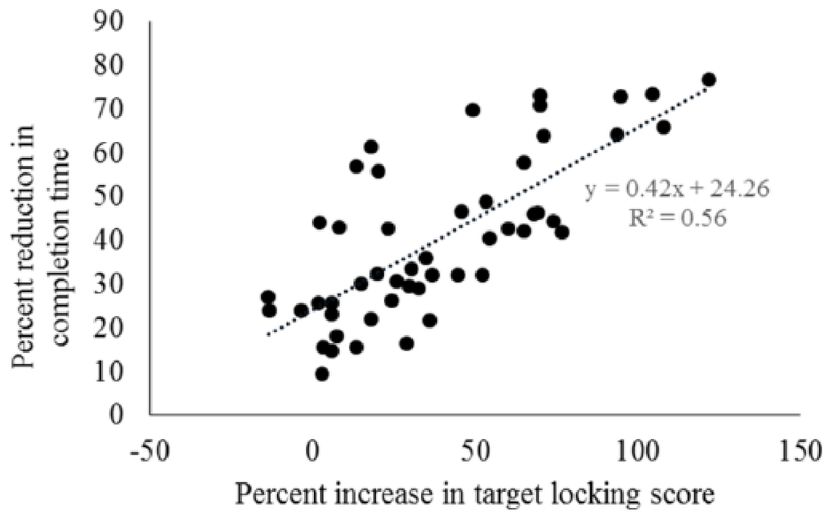

Figure 3. Relationship between percent reduction in completion time and percent increase in target locking score.

Discussion

In the present study we compared the effects of three types of action observation viewing instructions (AO+MI; AO; PO) and PP on the development of eye-hand coordination and performance of a novel visuomotor task. It was predicted that AO+MI instructions would lead to greater improvements in performance (i.e., reductions in completion time) and facilitate an earlier shift to a proactive gaze strategy than AO or PO instructions. The results of this experiment partially support our hypotheses. The AO+MI group improved their performance to a significantly greater extent than the control group, and these improvements were underpinned by changes in proactive gaze behavior. Specifically, after training, the AO+MI group exhibited higher target locking scores that were not significantly different to the PP group but significantly higher than the control group. A positive shift in target locking score indicates that more time is spent fixating targets than the cursor and is representative of increased top-down attentional control and superior eye-hand coordination (Sailer et al., 2005). Finally, the importance of the improvement in target locking score for the AO+MI group was reflected in the regression analysis that revealed a significant positive relationship between target locking score and task performance. This evidence suggests that the AO+MI intervention helped participants to develop more proactive, feedforward, gaze behavior and that this helped to improve their rate of visuomotor adaptation, compared to a control group.

These results can provide some support for Jeannerod's (2001) simulation theory. Although no central measures of brain activity were taken in this experiment, it is possible that by engaging in dual action simulation, the participants in the AO+MI group would have experienced increased activity in the motor regions of the brain during their training, than participants in the AO or PO groups, where no deliberate imagery was instructed. Based on the findings of Hardwick et al. (2018), the addition of motor imagery for participants in the AO+MI group would likely have evoked increased activity in the premotor cortex and supplementary motor area, as well as sub-cortically in the bilateral putamen and cerebellum. The AO+MI training may, therefore, have provided a closer behavioral match to action execution than occurred through either passive or active observation. This may have contributed to participants in the AO+MI group developing a task-specific motor representation that was more analogous to physical practice than the other simulation conditions, and is reflected in the achievement of a more proactive gaze strategy and improved performance of the AO+MI group.

Another possible explanation is that the inclusion of kinesthetic imagery alongside the AO stimulus may have facilitated the development of sensorimotor mapping rules that improved proprioceptive modes of action control. Specifically, while the AO component is thought to develop the sequencing and timing of basic action concepts (Wright et al., 2018), kinesthetic imagery has been shown to update the proprioceptive components of the forward model that subsequently improves movement planning and control (Kilteni, Andersson, Houborg, & Ehrsson, 2018). The development of more elaborate proprioceptive control is indicative of more expert-like motor control that ‘frees-up’ vision to be allocated as a feed-forward resource to guide action ahead of time (Sailer et al., 2005). In this explanation, due to the inclusion of kinesthetic imagery, the AO+MI group may have developed this proprioceptive ability to control the cursor skillfully without having to monitor it visually (compared to AO and PO groups) allowing them to locate and fixate targets ahead of time, thereby improving performance.

Finally, kinesthetic imagery has previously been shown to facilitate corticospinal excitability to a greater extent than visual imagery (Stinear, Byblow, Steyvers, Levin, & Swinnen, 2006). Subsequently the AO+MI training may have produced stronger activity in the premotor and motor regions of the brain than active or passive observation (Wright et al., 2016), which is widely believed to be advantageous for promoting neuroplastic changes that facilitate motor processes and behavioral outcomes (see Eaves et al., 2016). Future research may wish to explore the effects of AO+MI upon motor representations further by including explicit measures related to their generation and maintenance (Frank, Land & Schack, 2016).

From an applied perspective, whilst it is clear that physical practice offers superior performance benefits to all simulation conditions, AO+MI seems to facilitate significant improvements in performance and gaze behavior compared to no intervention. Conversely, active or passive observation strategies seem to offer no significant benefits for this type of task, compared to doing no intervention at all. These results provide interesting avenues for further research in clinical populations where individuals are unable to carry out physical practice due to illness, injury or disease. For example, while AO+MI interventions have been shown to increase corticospinal excitability (e.g., Wright, Williams, & Holmes, 2014), which may be linked to improvement in neural pathways supporting improved functional strength (Scott et al., 2017), they may also serve to facilitate the development of effective eye-hand coordination critical for activities of daily living (e.g., reaching and grasping). This would have significant clinical benefit for recovering stroke patients suffering hemiparesis or with patients after upper limb amputation. Future studies should aim to explore the use of AO+MI within these populations to support more traditional physical neurorehabilitation techniques.

While these findings are informative, some limitations need to be acknowledged. First, it is possible that if participants had been exposed to a longer training period, or had completed their action observation training alongside physical practice then greater improvements in performance or gaze control may have been revealed. However, AO+MI interventions of similar duration have been shown to improve performance in previous research (Bek et al., 2016). Finally, the MI ability of participants was not assessed in this study due to the current lack of a suitable measure for AO+MI imagery ability characteristics.

In conclusion, these findings suggest that AO+MI training can be used to facilitate an earlier shift to a proactive pattern of eye-hand coordination, similar to that observed in physical practice, during performance of a novel visuomotor task. Therefore, AO+MI may be an effective technique for restoring optimal eye-hand coordination in populations where physical practice is painful or impossible, such as in stroke or upper limb amputation, and future research should endeavor to explore the effects of AO+MI training on eye-hand coordination in these clinical groups.

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